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RESEARCH ARTICLE

The asymmetric and long-run effect of energy productivity on environmental quality in Ireland

Dervis Kirikkaleli[1] · James Karmoh Sowah Jr.[2] · Kwaku Addai[2]

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Abstract
This study aims to examine the long-run asymmetric impact of energy productivity on environmental quality in Ireland. The data set covers the period from 1990Q1 to 2019Q4. Although the border issue has been the source of contention and terrorism for decades in Ireland, the country is conscious of modern innovations and has a coherent body of environmental law. Ireland's goal is to achieve 80% of its electricity as renewable energy and reduce carbon emissions by 51% in 2030. Unlike earlier studies, the novelty of this study lies in the thorough analysis of how energy productivity affects the quality of the environment in Ireland while controlling for financial development, primary energy consumption, and economic growth utilizing the nonlinear ARDL approach and other robust econometric techniques. Precisely, the results indicate that (i) energy productivity benefits the environment by lowering CO_2 emissions (CO_2E) in the long term; (ii) financial sector development enhances the quality of the environment in Ireland; (iii) increase in primary energy consumption and economic growth without eco-friendly protocols propel an increase in CO_2E. These findings support the economic theory that energy productivity can stimulate steady green living and green technological growth. We recommend that policymakers in Ireland invest in energy productivity and prioritize R&D that embraces cleaner technologies and cross-cutting eco-friendly policies to combat environmental challenges in Ireland and the world at large.

Keywords Ireland · Nonlinear ARDL · Energy productivity · CO_2 emissions · Environmental quality

Introduction

In today's world, climate change and global warmings are the most pressing environmental concerns and controversial issues facing the global world. In fact, several climate scientists believe that rising greenhouse gas emissions, especially carbon dioxide emissions (CO_2E), are the most important factor driving climate change. It is generally accepted that countries have become aware of the negative consequences of increasing atmospheric carbon dioxide emissions levels and are taking appropriate measures to cope with image-related risks and extreme events around the world. It is estimated that around two-thirds of greenhouse gas emissions in the world are caused by the energy sector (Newell et al. 2021). Studies have reported that human activities are the main cause of ecological disturbances, global warming, climate change, and pollution of the environment (Nielsen et al. 2017) A key focus of the Paris Conference (COP-21) was to educate world leaders on the need for clean energy to save our planet (Salvia et al. 2021). Energy production and agriculture, in particular intensive livestock rearing, were identified as factors posing major environmental challenges in the Europe areas. The European Union (EU) has set binding targets to comply with COP-21 in Paris and to reduce greenhouse gas emissions by at least 40% in 2030 The vital element here is to understand how energy efficiency impacts CO_2E in achieving the United Nations goals set out in the

Responsible Editor: Ilhan Ozturk

✉ Dervis Kirikkaleli
dkirikkaleli@eul.edu.tr

James Karmoh Sowah Jr.
sowahjamesk@yahoo.com

Kwaku Addai
addaik71@gmail.com

[1] Faculty of Economic and Administrative Sciences, Department of Banking and Finance, European University of Lefke, Lefke, Northern Cyprus TR-10 Mersin, Turkey

[2] Faculty of Economics and Administrative Sciences, Department of Business Administration, European University of Lefke, Lefke, Northern Cyprus TR-10 Mersin, Turkey

Paris COP26. Although interrelated studies have received considerable attention, numerous factors have been identified as causative elements to climate change in the recent economics literature (Salvia et al. 2021). The results of these studies show that some toxic pollutants, such as phosphorus, sulfur dioxide, nitrogen, and others, have been found to be declining, yet the effects of CO_2E on the environment remain complex and controversial. Our planet is in danger of irreversible damage due to climate change, which must be addressed urgently. It is becoming increasingly difficult to reduce the adverse impacts of anthropogenic CO_2E on the environment. In this study, we examine the asymmetric and long-run effect of energy productivity on environmental quality in Ireland, spanning 1990Q1 to 2019Q4.

The Republic of Ireland is one of the 187 countries that ratified the "Paris agreement, which commits to limiting global warming to below 2 °C" (Huang and Zhai 2021). Ireland is an island nation on the westernmost edge of Europe, and after Great Britain, it is the second largest island on the continent (Colfer 2020). Ireland has wide expanses of lush, green fields, as the country is known for its lush landscape; in fact, it is commonly referred to as the Emerald Isle. A number of renowned writers have come from Ireland, including several Nobel Prize winners in literature. Unlike other European countries, the Irish have a profound affection for nature and rural living. The Irish government is committed to an innovative environment; it has established six national parks and hundreds of national heritage areas throughout the country. The €989 million recovery and resilience plan developed in Ireland in response to the Covid-19 pandemic plays a role in paving the way for a greener future. About 42% of the funding has been allocated for climate investments and reforms, €164 million for upgrading Cork commuter rail, and €155 million for energy efficiency measures in carbon neutrality throughout Ireland. The authority of Ireland operates closely with the Europe Union (EU) on ecological sustainability and clean technologies (Davies et al. 2021). Between 1992 and 2020 EU's flagship funding contributed around €90 million to 67 Irish projects. However, in Ireland, progress in delinking the economy from environmental pressures has been uneven over the last decade. During mid-2018, greenhouse gas emissions, waste generation, and nutrient pollution rose as a result of strong economic growth and as well as the inception of the Covid-19 pandemic In 2021, Irish power companies and industrial companies increased emissions by 15% or two million tonnes, while the overall in increased across Europe was 9.1% approximately.

In 2020, agriculture production increased Ireland's greenhouse gas emissions by 37.1%, and the transport sector contributed to the increase in CO_2E by 17.9%. The transport sector is known as the fastest-growing source of greenhouse gas emissions in Ireland since the 1990s. Statistics show that Ireland's 2020 GHG emissions were 58.77 million tonnes of CO_2E, the equivalent of Mt CO_2Eeq, which is 4.7% higher than 2021 CO_2E of 61.53 Mt CO_2Eeq. Further, environmental challenges such as pollution, chemical exposure, and underinvestment in drinking water infrastructure are the most pressing concern in Ireland. However, due to the global pandemic, there was a decrease of 3.4% in CO_2E in Ireland between 2019 and 2020. The statistics show that Ireland failed on its overall effort sharing regulations (RES) target for 2020 (Schenuit et al. 2021). Some time back, scientists warned Ireland society about the dangers of environmental collapse if stricter ecological policy measures are not implemented. In this study, we examine the asymmetric and long-run effects of energy productivity on environmental quality in Ireland while controlling for financial development, economic growth, and primary energy consumption, respectively.

Enhancing the efficiency of production and supply is essential for reducing greenhouse gas emissions (Salvia et al. 2021). Ireland is an energy-importing economy, hence it is important to note that efficient production and supply have direct and indirect environmental benefits. Recent studies on energy efficiency tell us that energy productivity measures the economic benefit we receive from each unit of energy we consume, cost-saving energy (Alola and Joshua 2020; Ali et al. 2022). Generally, energy productivity is calculated by dividing gross production or economic output (e.g., revenues or GDP) by the amount of energy consumed (e.g., kilowatt-hours of electricity or barrels of oil equivalent). Energy productivity is defined by both concepts, with the former being defined as GDP per unit of energy consumed and the latter as the amount of energy consumed per unit of production (Ali et al. 2022). Similarly, according to Huaman and Jun's (2014) study, energy productivity is a measure of the amount of money we save when we use alternative energy sources. According to mathematics, the total energy used in kilowatts per hour divided by gross energy produced per economic output gives the value of energy productivity. In particular, renewable energy consumption in kilograms of oil equivalent (Mtoe) can be calculated by multiplying the renewable energy consumption as a percentage of total energy consumption by the total energy consumption in kilograms of oil equivalent (Mtoe) (Mtoe) and then dividing by 100.

In addition, studies have shown that a variety of socioeconomic factors influence the demand for energy in developing and developed countries. For instance, trade, primary energy consumption, net capital income, and emerging technologies determine energy demand. In spite of this, the growth of primary energy consumption has offered numerous economic opportunities. Between 2005 and 2020, primary energy consumption from fossil fuels or oil continues as the dominant energy source, holding a 45% share of the 86% increase in primary energy consumption (World Bank 2019).

It remained flat in 2017, grew 1.6% in 2018 but shrunk from 49% share in 2019 due to the shock of the Covid-19 pandemic, and descended to 34% below 2005 consumption. The debate on primary energy consumption and global CO_2E has recently gained more attention as an academic subject. There is a diminutive consensus that primary energy consumption has caused irreversible environmental damage (Hasanov et al. 2018).

Further, creating pathways toward sustainability requires transforming the financial sector and production patterns to cost-saving environmental technologies (Sawyer 2015). Financial development has played a crucial role in the prosperity and expansion of the country's economy. However, studies provide that financial development is one of the critical factors that is increasing energy demand worldwide and subsequently increasing greenhouse gas emissions (Meles et al. 2022). Although numerous empirical literature proved that financial development could increase CO_2E from a global perspective, many questions remain unanswered regarding the theoretical perspective of assessing the long-run effect of energy productivity on environmental quality. According to the theoretical analysis, the influence of financial development on CO_2E is uncertain. Overly expansionary monetary policy and ultra-low interest rate policies to boost growth could have adversely affected the environmental quality. Financial development funds for innovative and environmentally friendly activities are likely to reduce CO_2E. In sum, the overall impact is determined by the relative size of the negative and positive effects. In this study, we assess Ireland time series selected datasets since, in fact, it has been ignored by previous studies.

Due to the aforementioned, the present study contributes to the growing body of empirical literature with its determination of the asymmetric effects of energy productivity on environmental quality in Ireland, particularly in relation to financial development, economic growth, and primary energy consumption by utilizing nonlinear autoregressive distributed lag (NARDL) bounds test and robust econometric methodologies. The study uses Ireland's analysis in order to be consistent with the analysis of Easterlin. The evidence indicates that a unit of energy productivity produces a larger impact on environmental quality. This paper argues that the asymmetric effects of energy productivity on environmental quality in Ireland provide an explanation for the Easterlin paradox, or energy productivity is a more sensible goal for economic energy policy because it can lead to secure living conditions that form the foundation on which everyone can pursue happiness. The theory of asymmetric information argues that policy may fail due to an imbalance in the information available to policymakers (Wang et al. 2020). Unlike an older approach to cointegration, the nonlinear bounds test of cointegration has advantages over its alternatives. The major three are the following: (i) it can assess appropriateness variables through asymmetric error correction terms (ECM-based tests); (ii) also allows mixed regressors of I (1) and I (0) (Shin et al. 2001); and (iii) using this method, the long-run relationship among the variables can be decomposed, and a distinction can be made between positive and negative shocks. Further, Fourier ADL cointegration analysis was used to capture the unknown number's hidden effects and control for nonlinear structural breaks. To determine whether variables have a causal relationship, we applied the frequency domain causality test and followed by several econometric robustness tests, namely the cumulative stability test proposed by Brown et al. (1975) and Breusch-Godfrey serial correlation LM tests (Sowah & Kirikkaleli 2022). To our knowledge, these robust methodologies are relatively new, and they have not been implemented in such a context for Ireland. Hence, the study is significant in that it will serve as promising policy tool to lower greenhouse gas (GHG) emissions by reducing energy costs in Ireland. The remainder of this article summarizes the literature review, methodology, results and discussion, and policy implications.

Literature review

This section aims to discuss the applicable theoretical arguments in support of the topic and to shed some light on some of the controversies surrounding the empirical findings in the selected literature review. The paper examines energy productivity's asymmetric and long-run effects on the quality of Ireland's environment. Ireland is an island nation; it has an open economy and a large industrial sector. Ireland as the country was among the first country to ratify the Paris agreement, and it has set a goal of becoming carbon neutral by 2030. Growing evidence indicates open economies, and large industrial nations are major contributors to greenhouse gas emissions (Sowah & Kirikkaleli 2022; Nevzorova & Kutcherov 2019). Based on theory, the rebound effect, neoclassical growth models, the general equilibrium model (GEM), and alternative policy evaluation models are inconclusive. It has become increasingly important for economists and policymakers to understand the impact of energy productivity on CO_2E in a carbon-intensive country like Ireland. In this study, we assume that achieving the target of reducing CO_2E will require significant investments in innovative energy technologies, patents on environmental innovations, and conversion, as well as measures to control the demand for energy. This study follows a report from Sarkodie and Strezov (2019), Huan et al. (2022), Djellouli et al. (2022), Umar et al. (2021), Yu-Ke et al. (2022), Debone et al. (2021), Nevzorova and Kutcherov (2019), Mishra and Smyth (2017), Rjoub et al. (2021), Adams et al. (2018), Usman et al. (2021), Hao et al. (2021), Ding et al. (2021), Hassan et al. (2021), Li et al. (2020), Kirikkaleli and Sowah (2022), Chen et al. (2019), and Sun et al. (2022) among others to provide a synopsis of empirical evidence explored between countries' economic and environmental variables in a variety of areas including criticisms that have been suggested against these studies.

In response to the desire to gain a deeper understanding of the range of impacts on Ireland's environment as well as issues arising from inconclusive empirical findings, this study examines the following research questions: (i) what role does energy productivity plays in reducing CO_2 emissions in Ireland?; (ii) is there a significant effect of primary energy consumption, financial development, economic growth on CO_2 emissions in Ireland? The answers to these above study questions are empirically hypothesized and are crucial for Ireland in a plethora of ways (a) the study questions may aid the process of forming a policy direction that promotes low-carbon emissions in Ireland. (b) Secondly, the second question will assist in providing relevant empirical insights on economic growth, financial development, primary energy consumption, energy productivity, and the quality of the environment (measured by CO_2 emissions). In this study, we summarize and hypothesize the relationship between financial development, primary energy consumption, economic growth, energy productivity, and CO_2 emissions based on previous studies, as they are detailed below.

Energy productivity—is a relatively new phenomenon, and it simply refers to the economic benefits that can be derived from using total primary energy sources. It measures \$/MJ and captures an economy's total primary energy consumption (TPES). Nevzorova and Kutcherov (2019), Ding et al. (2021), and Yu-Ke et al. (2022) are among the recent studies that focused on the effects of energy productivity on CO_2E. Li et al. (2020) examined energy productivity and renewable energy consumption on CO_2E in OECD economies. It is shown that they have a positive relationship with each other. Yu-Ke et al. (2022) analyzed the determinants of energy productivity in 39 countries between 1995 and 2009. According to this study, increased sectoral energy productivity was the primary factor responsible for increasing economic stability. However, Nevzorova and Kutcherov (2019), and Ding et al. (2021) studies criticized the essential influences of energy productivity for being slowed and imped by a range of interrelated barriers in many countries. They pointed out that if barriers, such as unprecedented demand for energy, are mitigated, then energy productivity can enhance the environmental quality. Based on overwhelming empirical support in favor of energy productivity, we formulate the below hypotheses (1):

Hypothesis 1 (H_{o1}): energy productivity has positively enhanced CO_2 emissions.

Generally, it is believed that the unprecedented demands for energy consumption negatively affect the environmental quality (Cai et al. 2022; Ding et al. 2021). Ireland, as the country's net energy largely, comes from four different sources: natural gas, renewable, solid fossil fuels, and petroleum products. In 2020, petroleum products accounted for 49.9% of Ireland's energy mix, and it is the most dominant source by far. Higher use of biofuels combined with an increase in wind power production has been encouraged and is the main reason for the increase in energy surplus in Ireland over the past year. In terms of energy export, in 2018, Ireland exported 4.568, 100 1000 KW/H to the UK and 2,367,740 1000 KW/H to Luxembourg, respectively. Thus, the Irish government has always placed a high priority on energy security. In line with Europe law, Ireland has committed to convert 100% of its electricity to renewable sources by 2040. Hence, this study assumed that a steady increase in energy productivity has significantly reduced CO_2E in Ireland, i.e., $\vartheta_1 = \frac{\vartheta LCO_2E}{\vartheta LEP_{it}} < 0$; Yu-Ke et al. (2022) and Li et al. (2020) support this hypothesis.

An active financial sector is essential for economic well-being and is a prerequisite for the success of the private and public sectors. Precisely, it measures commercial banks' assets and equity capital as a share of GDP growth. Recent evidence on financial development shows that it increased CO_2E through two major channels (Rjoub et al. 2021; Huan et al. 2022, Adams et al. 2018). (1) The development of the stock market can lower the cost of a financing loan, and (2) growth in fixed capital formation can allocate new company investments. Using an augmented mean group approach, Usman et al. (2021) looked at the impact of financial development and financial inclusion on CO_2E in the 15 highest emitting countries in the world, including Turkey and China. The study found that financial sector development funds innovative environmentally friendly projects in Chinses cities, thereby significantly reducing the environmental pollution. A similar study by Adams et al. (2018) on Turkey found supported Usman et al. (2021) findings. Adams et al. (2018) study noted that financial development leads to an increase in FDI inflows into Turkey and subsequently increased investment in R&D innovations. In contrast, Doytch and Narayan (2016) study found ambiguous findings on the same subject. Based on these empirical outcomes, we formulate hypotheses (2):

Hypothesis 2 (H_{o2}): financial developments reduce CO_2 emissions.

Over 40 years, global financial institutions such as investment managers, international banks, insurers, and aircraft leasing have made Ireland their home (Byrne 2020). Nevertheless, there is still controversy about the specific influence of financial development on CO_2E (Mishra & Smyth 2017). The issue is raising environmental concerns in many countries, including Ireland. It is imperative that Ireland fosters a strong recovery of its financial sector as part of its recovery and resilience plan. Exports of financial services rose by 2.1% in 2020, totaling €17.2 billion. In the same year, the mortgage market increased by 8.11% (Meles et al. 2022). Further, households' consumption loans rose to €11.5 billion in 2021. The households' saving rate rose from 11.04% in 1999 to reach an all-time high of 34.53% in 2020 and a record low of 10.34% of GDP in 2019 (Meles et al. 2022). Based on these facts, we assumed that financial development had reduced CO_2E in Ireland, i.e., $\vartheta_2 = \frac{\vartheta LCO_2E}{\vartheta LFD_{it}} < 0$; Adams et al. (2018) and Usman et al. (2021) studies support this hypothesis.

In both developing and non-developing countries, energy is a key strategic issue. Over the past three decades, global primary energy consumption has doubled. Basically, a country's primary energy consumption is a measure of its overall energy demands. Primary energy consumption is divided into three categories: (1) losses of energy during transformation (e.g., oil or gas into electricity), (2) consumption of energy by the energy sector itself, and (3) distribution of energy to end users for final consumption. In 2010, fossil fuels provided 90% of the world's total primary energy consumption (WTPEC), in which oil contributed 34.77%, natural gas contributed 23.76%, and coal contributed 29.36%, while 5.47% of the energy was derived from nuclear fuels and 6.63% from hydroelectricity. Sarkodie and Strezov (2019), Djellouli et al. (2022), and Umar et al. (2021) are among the empirical studies that have assessed the effects of primary energy consumption on CO_2E in recent times. Umar et al. (2021) study on the United States transport sector shows that fossil fuel consumption significantly increased CO_2E from 1981 to 2019. Similarly, Djellouli et al. (2022) panel research on African countries supported Umar et al. (2021) study findings. In contrast, Sarkodie and Strezov (2019) study failed to provide any significant evidence based on the datasets covered. Based on this evidence, we assumed that primary energy consumption had increased CO_2E in Ireland; hence, we formulate hypotheses (3):

Hypothesis 3 (H_{o3}): primary energy consumption increases CO_2 emissions.

Today in many countries, the main sources of energy are oil, coal, and natural gas. All of these elements are fossil fuels, unsustainable, and contribute to environmental pollution (Azam et al. 2022; Zakari et al. 2022). Ireland's target is to limit primary energy consumption up to 80% renewable electricity and a 30% reduction in CO_2E. There is no simple way to determine whether energy consumption leads to a loose or strict policy or whether primary energy consumption adversely affects environmental quality in Ireland over the long term. Energy-related CO_2E by homes in 2020 was 5.5 tonnes. Of this total direct fuel consumption accounted for 73%, and indirect fuel (electricity) consumption accounted for 27%. A total of 61.53 million tonnes of carbon dioxide was emitted in 2021, representing a 4.7% increase over 2020. However, emissions for 2020 decreased by only 3.4% compared to 2019. These results show that Ireland did not meet its 2020 effort-sharing regulations (RES) target (O'Gorman 2020). Based on these facts, this paper assumed that primary energy consumption increased CO_2E in Ireland, i.e., $\vartheta_3 = \frac{\vartheta LCO_2E}{\vartheta LPEC_{it}} > 0$, Umar et al. (2021) study supports these findings.

The economy's growth inevitably results in higher pollution levels simply due to increased output (Debone et al. 2021). It is the most widely recognized factor that drives an increase in CO_2E. As it is noted in the economics literature (Hassan et al. 2021; Debone et al. 2021), the usage of fossil fuels, renewable resources, labor, and commercial policy to satisfy alternative investments has exerted positive pressure on global CO_2 emissions. Chen et al. (2019), Sun et al. (2022) Debone et al. (2021), and Kirikkaleli and Sowah (2022) are among recent studies on the country's economic growth. A country-specific study by Kirikkaleli and Sowah (2022) on the Liberian economy shows that financial liberalization variables such as saving deposit interest rates, gross investment, etc., significantly and positively impacted economic growth and consequently increased greenhouse gas emissions. Debone et al. (2021) study reported that the use of fossil fuels to satisfy alternative investments had increased the level of CO_2E in developing countries. However, Chen et al. (2019) and Sun et al. (2022) did not find any significant interrelationships between economic growth and carbon dioxide emissions. It is most common for economic growth to exhibit scale effects (Chen et al. 2019; Kirikkaleli and Sowah 2022); hence, we formulate hypotheses (4):

Hypothesis 4 (H_{o4}): economic growth increases CO_2 emissions.

It is very difficult and complex to predict the effects of economic growth on CO_2E. Research on the growth process has generally produced mixed results (Debone et al. 2021; Chen et al. 2019). In some cases, researchers support economic growth as having a positive impact on society, while in other cases, they assert that a higher rate of economic growth will result in a higher level of carbon emissions. In Ireland, the GDP growth rate was 3.4% in 2020, it jump to 4.8% in 2021, and in 2022 first quarter of real GDP grew by 10.8%. However, the projection for 2023 shows GDP growth will shrink by 2.7%. Hence, we assumed that economic growth has positively increased CO_2E in Ireland, i.e., $\vartheta_3 = \frac{\vartheta LCO_2E}{\vartheta LGDP_{it}} > 0$; the studies of Hao et al. (2021) and Debone et al. (2021) support this hypothesis, contrary to Sun et al. (2022) and Chen et al. (2019) studies.

Study data sources and methodology

Study data sources

This study examines the asymmetric and long-run effect of energy productivity on environmental quality in Ireland while controlling for economic growth, financial development, and primary energy consumption spanning from 1990Q1 to 2019Q, which consists of two decades of data. The data have been extracted from the Organization for Economic Cooperation and Development (OECD) databases and are updated quarterly (i.e., transformed data using Eviews10). The carbon dioxide emissions (CO_2E) measured in metric tons are selected as the dependent variable and are the determinant of environmental quality (Djellouli et al. 2022; Sun et al. 2022). Economic growth (GDP), energy productivity (EP), primary energy consumption (PEC), and financial development (FD) are explanatory variables, and they were selected based on theories and empirical evidence (Debone et al. 2021; Umar et al. 2021). These variables have their individual human-related activities in intensifying CO_2E concentrations in the atmosphere. GDP measures per capita 2010 US $ constant, FD measures financial depth, including the stock of private credit and market capitalization as a percentage of GDP while PEC measures the primary energy consumption demand of a country. EP is our core explanatory variable, a relatively new phenomenon that measures the economic benefit of end users' final energy consumption. We express all data in natural logarithm form to avoid scaling issues (Sun et al. 2022). Table 1 presents the descriptive statistics, while the flowchart is presented in Fig. 1.

Table 1 Descriptive statistics

Study period	1990Q1–2019Q4				
Data source	OECD				
Code	LCO_2E	LGDP	LEP	LFD	LPEC
Mean	1.604206	11.23847	4.175036	−0.173710	2.211484
Median	1.594598	11.30094	4.183983	−0.172189	2.236772
Maximum	1.684419	11.57311	4.490440	−0.098738	2.298847
Minimum	1.511626	10.90416	3.955745	−0.306565	2.059403
Std. Dev	0.051952	0.192319	0.148803	0.050461	0.067719
Skewness	0.052332	−0.263446	0.352578	−1.076883	−0.877175
Kurtosis	1.821686	2.111995	2.254186	3.774750	2.419467
Jarque–Bera	6.996887	5.330839	5.267426	26.19472	17.07380
Probability	0.030244	0.069570	0.071811	0.000002	0.000196

OECD. Source: authors' computation

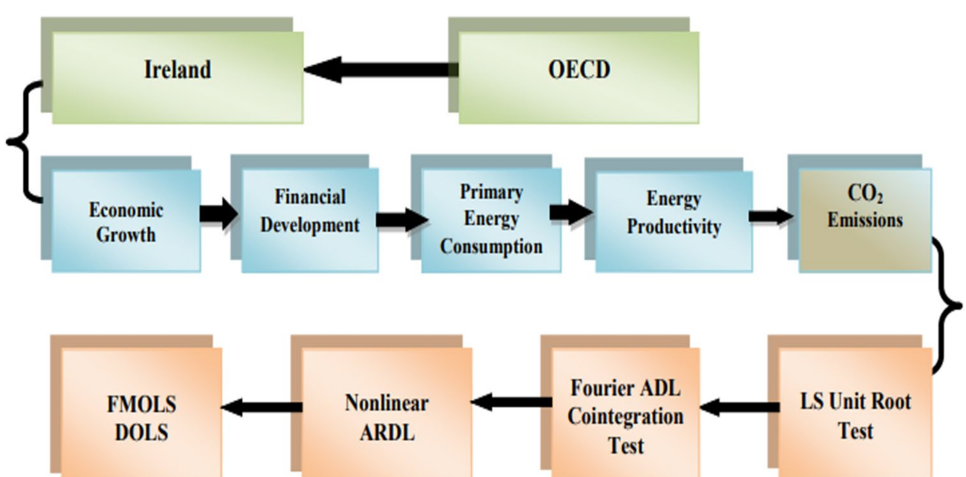

Fig. 1 Flowchart of the study. Source: authors' computation

Methods of estimation and models

Research has been conducted on how variables, such as energy, environment, and economic growth, are interconnected, such as energy, environment and economic growth. It is essential to note that energy productivity has been relatively understudied in terms of its importance in managing CO_2E. Likewise, there is no empirical analysis of the subject in the literature for the Ireland economy. We extend Shin et al. (2014) NARDL model by including energy productivity (EP) as a key factor. Based on the broad approach to the extended neoclassical growth model, the below Eqs. (1, 2, and 3) are an illustration of how the variables are specified:

$$CO_2E = f(\mathrm{EP}, \mathrm{PEC}, \mathrm{GDP}, \mathrm{FD}) \tag{1}$$

In order to conduct the empirical analysis, all variables are transformed into natural logarithms:

$$LCO_2E_{it} = \vartheta_0 + \vartheta_1 LEP_{it} + \vartheta_2 LPEC_{it} + \vartheta_3 LGDP_{it} + \vartheta_4 LFD_{it} + \varepsilon_{it} \tag{2}$$

where t indicates time, i represents linearity units. CO_2E_{it} depicts carbon dioxide emissions, EP_{it} denotes energy productivity, PEC_{it} refers to primary energy consumption, GDP_{it} denotes GDP per capita 2010 US $ constant, FD_{it} refers to financial development, ϑ_0 is the constant term and the standard error term is represented by ε_{it}. Further, the NARDL) model application of positive (POS) and negative a (NEG) shock of our treated variables are:

$$\begin{aligned} LCO_2E_{it} &= \vartheta_0 + \vartheta_1 LEP^+_{1t}, LEP^-_{1t}, +\vartheta_2 LPEC^+_{2t}, LPEC^-_{2t} \\ &+ \vartheta_3 LGDP^+_{3t}, LGDP^-_{3t} + \vartheta_4 LFD^+_{4t}, LFD^-_{4t} + \varepsilon_{it} \end{aligned} \tag{3}$$

In this situation, the dependent variable increases (+) or decreases (−) as a result of the independent variables. Figure 2 presents the study framework.

Unit root tests

As an initial test, we capture the integration order of our selected time series variables using the LS unit root test with structural breaks. Most often, structural breaks have been neglected in previous studies (Perron 1994), which has caused unit root tests to be biased towards a false null hypothesis. It is imperative to employ the most relevant unit root test. After determining the integration of the order of the variables, we preceded with the Broock et al. (1996) BDS test to detect our dataset's stochastic hidden nonlinear patterns (dependence/independence). It is applied to take into account different embedding dimensions, i.e., ranging from 2 to 6. BDS test has a number of advantages over other alternatives (Harvey et al. 2008). The two most important advantages are that it guides against model misspecification and judgmental error. The econometric application is defined as:

$$BDS_{mT}(\varepsilon) = T^{1/2}[C_{m,T}(\varepsilon) - C_{1,T}(\varepsilon)\mathrm{m}]/\delta_{mT}(\varepsilon) \tag{4}$$

where T presents the sample size, ε is chosen proximity parameter, and $\delta_{mT}(\varepsilon)$ is the standard sample deviation of the statistical numerator that varies with dimension "m".

Cointegration tests

To capture cointegration among the times series variables, we employed the Fourier ADL cointegration test, which was developed by Banerjee et al. (2017). The Fourier ADL cointegration test allows the present study to test the existence of cointegration by taking into account structural breaks of unknown number, time, and structure. As a result, this method offers more effective results than VECM analysis in the following ways: it can take into account a relatively small number of observations, it does not lose

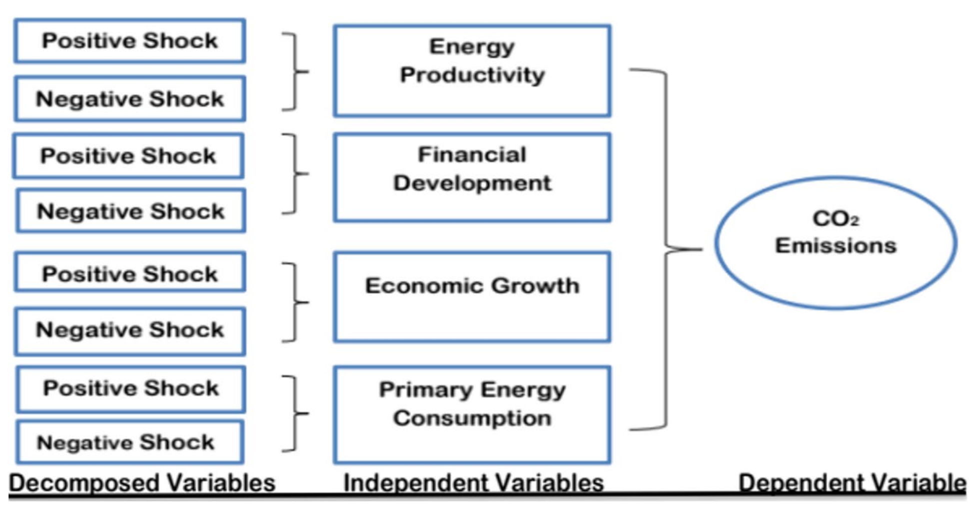

Fig. 2 Study Framework. Source: authors' computation

power due to the use of many dummy variables, and structure breaks are captured with a time-varying constant term (Liu et al. 2022a); the econometric application is:

$$\Delta y(t) = \alpha_0 + \partial_1 Sin(\frac{2k\pi t}{T}) + \vartheta_2 COS(\frac{2k\pi t}{T}) + \partial_3(Yt - 1 + \omega xt - 1) + \partial_4 \sum_{i=1}^{q} \Delta y_{t-1} + \partial_5 \sum_{i=1}^{p} \Delta xt - I + Z_t \quad (5)$$

where α_0, ∂_1, ϑ_2, ∂_3, ∂_4, and ∂_5 present the parameters, i is a particular lag length, q and p are the maximum allowed lag lengths, and Z_t is an error term. AIC and SIC determine the optimal lag length.

To estimate the long-run relationship, this study utilizes the nonlinear ARDL bounds test of cointegration. According to Kapetanios et al. (2011), this test gives more robust and reliable results. In contrast to traditional cointegration methods, this model has several advantages over its alternatives; (i) it can handle the appropriateness variables through error correction terms (ECM-based tests); (ii) it can decompose and distinguishes between positive shocks or increases (+) and negative shock or decreases (−) of each independent variable of X_{it} shocks among the variables; (iii) it can allow mixed regressors of I (1) and I (0) integration order (Shin et al. 2014). The long-run asymmetric cointegrating is written as:

$$Y_t = \beta_o + \beta_1^+ X_t^+ + \beta_1^+ X_t^- + \mu_t \quad (6)$$

where x_t^+ and x_t^- are the partial sums of positive and negative changes in x_t. Long-run asymmetric effects of X_1 on Y is calculated using $L_{M1+} = \frac{-\varphi_1^+}{\rho}$ and $L_{M1-} = \frac{-\varphi_1^-}{\rho}$.

In the economics literature, cointegration among estimated variables does not justify causality. To prevent spurious conclusions suggested by Geweke (1982), a frequency domain causality test developed by Breitung and Candelon (2006) was used in this study. This model has advantages over Dolado and Lütkepohl (1996), Banerjee et al. (2017), etc., in that it determines whether a particular component of the "cause" variable at frequency ω is useful in predicting the composition of the "effect" variable at the same frequency one period ahead. The mathematical application is as follows:

$$\chi_t = C_1 + \sum_{j=1}^{p} \alpha_j \chi_{t-j} + \sum_{j=1}^{p} \beta_j y_{t-j} + \sum_{j=1}^{p} \lambda_j Z_{t-j} + \mu_t \quad (7)$$

where $\alpha_j = \theta_{11,j}$ and $\beta_j = \theta_{12,j}$. The null hypothesis of $M_{y\rightarrow x}$ $(\omega) = 0$ is equivalent to

H_0: R(ω)β = 0

Robustness check test

Following examples from Kapetanios et al. (2011) and Banerjee et al. (2017), this study adopts two cointegrating regression robustness models, namely fully modified ordinary least squares (FMOLS) and dynamic ordinary least (DOLS). These estimators are parsimonious tools to measure the cointegrating slope between integrated variables in the presence of endogenous feedback and correct the first-order OLS bias to the extent necessary to provide a nuisance parameter-free asymptotic distribution and they serve as operating baseline robustness check estimators in this study.

Empirical analysis and discussions

Unit root outcomes

In our study, we examine energy productivity's impact on CO_2 emissions in Ireland as well as primary energy consumption, financial development, and economic growth. As an initial test, we capture the integration properties of the time series variables using the LS unit root test with a breakpoint. The results of the LS unit root test with a breakpoint are presented in Table 2. The results indicate that none of the series were stationary at level I (0). However, all variables became stationary when the first difference, level I (1), was introduced, as shown in Table 2.

After applying the Lee and Strazicich unit-root test as part of the initial assessment, we proceeded with the Broock et al. (1996) BD test to detect our stochastic hidden nonlinear patterns (dependence/independence) datasets. Table 3 presents BDS test outcomes; it shows that *z*-statistics values are far bigger, i.e., > BDS critical values. This implies that variables are non-linearly dependent in Ireland.

Cointegration test outcomes

The BDS model outcome steps the stage for us to proceed with a nonlinear-ARDL bound test of cointegration and Fourier ADL cointegration tests. These cointegration models can correct and better handle model misspecification, structural breaks, autocorrelation, and heteroscedasticity problems that are often ignored by Johansen and anger-granger cointegration tests (Zhang et al. 2022). Furthermore, comparing two cointegration models can improve estimation efficiency and mitigate the problem of weak tools and limited sample errors. Table 4 presents cointegration test outcomes; the NADL bound test of cointegration shows that the *f*-statistic of 3.436050 > upper bound critical value of 2.85 at a 5% significance level (Banerjee et al. 2017). This implies that GDP growth, primary energy consumption, financial development, energy productivity, and CO_2E have long-run equilibrium cointegration relationships in Ireland for the study period covered. Likewise, the Fourier ADL cointegration test confirms cointegration among our treated

Table 2 Unit root tests

At level						
		LCO_2E	LGDP	LEP	LFD	LPEC
LS	*t*-statistic (tau)	−4.412999	−3.546162	−3.977518	−4.373825	−4.470082
	Break points	1999Q1 2009Q3	1998Q4 2009Q3	2007Q3 2015Q4	2000Q3 2009Q4	1997Q4 2010Q1
Test critical values	1% level	−6.132933	−6.132933	−5.946953	−6.032800	−6.132933
	5% level	−5.515020	−5.515020	−5.454980	−5.484580	−5.515020
	10% level	−5.238640	−5.238640	−5.164287	−5.239060	−5.238640
At first difference						
		LCO_2E	LGDP	LEP	LFD	LPEC
LS	*t*-statistic (tau)	−6.086523	−6.253088	−7.967360	−7.605354	−5.772163
	Break points	2000Q3 2013Q3	2007Q1 2013Q3	2007Q1 2013Q2	2001Q2 2002Q4	2000Q3 2013Q3
	1% level	−6.005933	−5.939867	−5.939867	−6.002600	−6.005933
	5% level	−5.425867	−5.449800	−5.449800	−5.360067	−5.425867
	10% level	−5.150267	−5.159533	−5.159533	−5.048133	−5.150267

*, **, and *** represent 10%, 5%, and 1%. TB1 represents the break dates of the Perron and Vogelsang

Table 3 BDS test

Dim	BDS stat	Std. error	*z*-stat
LCO_2E			
2	0.188646***	0.003871	48.73511
3	0.315966***	0.006141	51.45477
4	0.400396***	0.007295	54.88877
5	0.456182***	0.007583	60.15989
6	0.491562***	0.007292	67.41049
LGDP			
2	0.204470***	0.004875	41.94167
3	0.346816***	0.007773	44.62067
4	0.446616***	0.009281	48.12161
5	0.517110***	0.009698	53.32055
6	0.567618***	0.009375	60.54275
LEP			
2	0.193646***	0.004975	38.92376
3	0.323886***	0.007910	40.94894
4	0.414269***	0.009418	43.98601
5	0.477075***	0.009814	48.61091
6	0.522166***	0.009461	55.18943
LFD			
2	0.190441***	0.009375	20.31287
3	0.318849***	0.014997	21.26090
4	0.402383***	0.017981	22.37860
5	0.454822***	0.018872	24.09985
6	0.486366***	0.018330	26.53383
LPEC			
2	0.205559***	0.006951	29.57338
3	0.350175***	0.011111	31.51582
4	0.451125***	0.013307	33.90122
5	0.521105***	0.013949	37.35856
6	0.569540***	0.013528	42.09983

***, **, and * represent 1%, 5%, and 10% level of significant, respectively. Dim. and Stat. denote dimension and statistic

Table 4 Fourier ADL cointegration and nonlinear ARDL bounds tests

Bounds test				
F-bounds test		Null hypothesis: no levels relationship		
Test statistic	Value	Signif	I (0)	I (1)
			Asymptotic: $n = 1000$	
F-statistic	3.527378	10%	1.85	2.85
k	8	5%	2.11	3.15
		2.5%	2.33	3.42
		1%	2.62	3.77
Fourier ADL cointegration test				
Test statistic		Frequency	Min_AIC	
−5.660005		2	−8.171290	

*, **, and *** denote 10%, 5%, and 1% significance level. We make decisions based on the critical values proposed by Banerjee et al. (2017)

Table 5 Nonlinear-ARDL long run form

Variable	Coefficient	Std. Error	*t*-statistic	Prob
LGDP_POS	0.598208**	0.291042	2.055399	0.0426
LGDP_NEG	1.278220**	0.589420	2.168606	0.0326
LEP_POS	−0.881443***	0.262941	−3.352248	0.0011
LEP_NEG	−1.433007***	0.533402	−2.686543	0.0085
LFD_POS	−0.033343	0.093579	−0.356305	0.7224
LFD_NEG	−0.299483**	0.123166	−2.431534	0.0169
LPEC_POS	0.382940	0.332696	1.151018	0.2526
LPEC_NEG	0.627657*	0.350454	1.790982	0.0764
C	1.506615***	0.008272	182.1235	0.0000
CointEq (−1)*	−0.125038***	0.020131	−6.211336	0.0000

*, **, and *** denote 10%, 5%, and 1% significance level

variables at a 1% significant level (Banerjee et al. 2017). Faisal et al. (2021) study supports these results.

NARDL bounds test outcomes

Following a robust econometric analytical pathway, Table 5 provides the full empirical results of the asymmetric and long-run effect of energy productivity on the quality of the environment in Ireland with unidirectional-forwards stepwise regressions. The regression for non-linearly tests was significant at the 1% level; misspecification tests proved that the nonlinear-ARDL bound tests specification was appropriate. The nonlinear-ARDL bound tests and Fourier ADL cointegration tests show long-run cointegration, and the estimated models are efficient. We continued to determine whether the difference between the coefficients of positive (POS) and negative (NEG) changes had the same magnitude (symmetric effect) or a different magnitude (asymmetric effect) and if they were statistically significant, as indicated in Table 5.

The outcomes of the regression showed that energy productivity (EP) reduces CO_2E, as the coefficients are negative and significant at the 1% level. It indicates that a 1% increase in EP reduces CO_2E by 88.144% while 1% decrease in EP declines CO_2E by 143.301%. This implied that energy productivity use as a policy tool could mitigate Ireland's environmental degradation effects. Higher use of biofuels combined with renewable energy sources, wind power production, patents on technologies, and solar systems innovations are the main pathway for sustaining a low-carbon society in Ireland. The Irish government has always placed energy security at the forefront of its policies. Other energy challenges such as burning fossil fuels to agricultural power production, homes, mechanical, and industries should be a factor in green living. A 1% decline in energy productivity would result in a 143.301% decline in the quality of the environment across Ireland. Further, the stepwise regression also showed that conclusion of this study was not affected by the control variables employed. This outcome supports studies conducted by Yu-Ke et al. (2022) and Li et al. (2020) and Hypothesis 1 in this current study.

The effect of financial development on CO_2 emissions is uncertain, according to economic theories. Some researchers (Khan et al. 2020; Umar et al. 2020; Ali et al. 2022) consider that FD could fund innovative activities which improve could environmentally friendly projects, thereby reducing carbon emissions. While other believe that FD could stimulate demand for energy consumption, and expand scales of production, thereby increasing carbon emissions. Based on these perspectives, this study assumed that the PSO and NEG shocks in FD negatively affected CO_2E in Ireland in the long term. Researchers have expressed conflicting viewpoints regarding the impact of financial development on CO_2 emissions. According to this study, a 1% unit increase in financial development causes CO_2E to decline by 3.334% in Ireland, but statistically insignificant. While a 1% decrease in financial development causes the quality of the environment in Ireland to decline by 29.948% and is statistically significant at a 5% level. The overall total impact is determined by the relative size of financial development, negatively reducing CO_2E. This can most often be attributed to financial development funding innovative enterprises that are highly polluting. For instance, among other things, energy demand for the transportation and tourism sectors, scale expansion of food and tobacco processing, and toxic chemical release emissions pose a significant risk to the environment. These results show that financial development acted more as reducing than promoting CO_2E. These outcomes support Ali, et al. (2022), Umar et al. (2020) empirical findings, and Hypothesis 2 of the current study.

Economic growth is defined as an increase in the quantity and quality of goods and services produced and consumed by society. However, growth momentum is losing steam; it has been criticized as the driver of income inequality, primary energy consumption, depleting natural resources, deforestation and extreme weather conditions, and recently, greenhouse gas emissions, among others (Liu et al. 2022b; Debone et al. 2021). This current study assumed that GDP growth is the driving force of CO_2E in Ireland. The study outcomes showed that a positive and negative shock to economic growth positively impacts environmental quality in Ireland. To put it another way, a 1% increase in economic growth cause environmental pollution to increase by 59.821%, while a 1% decrease in economic growth causes Ireland's environmental quality to increase by 127.822%, all statistically significant at 5% levels. In other words, a positive growth rate of CO_2 emissions enhances the quality of the environment in Ireland. A renewed focus has been directed toward the decomposition of the decoupling of carbon emissions from economic growth in recent years. What really matters in the decoupling scenario is when the growth rate positively affects CO_2 emissions. This outcome collaborates with Nasir et al. (2019) and with Hypothesis 4 in this paper. Particularly, developing countries have experienced negative environmental impacts due to their economic growth (Chen et al. 2019; Sun et al. 2022).

The world has suffered severe environmental deterioration over the years and environmental problems directly related to primary energy consumption and energy production to satisfy industrial demand. Djellouli et al. (2022) study reported that air pollutants from fossil fuel combustion are causing major environmental challenges in Ireland. With regards to primary energy consumption data, both POS and NEG shock in primary energy consumption; there positive effects on CO_2 emissions in Ireland. In other words, a 1% increase in primary energy consumption use propels the quality of the environment to decline by 38.294%, while a 1% decrease in primary energy consumption use causes the quality of the environment to increase by 62.766% in real terms. This finding supports Hypothesis 3 in this current study and the study by Djellouli et al. (2022) and Umar et al. (2021), respectively. The study of Umar et al. (2021) shows that primary energy consumption from fossil fuels significantly increases CO_2E in the USA. Besides primary energy consumption, other environmental issues such as thermal pollution, water pollution, and solid waste disposal need to be managed. Further, findings from NARDL ECM-based test values of (−0.213436) variations suggest that variables are cointegrated in the long run, and the allover effects are asymmetric (Shin et al. 2014), as indicated in Table 5.

Robustness checks test outcomes

Table 6 presents the results of the DOLS and FMOLS models used as baselines for robustness testing (Kirikkaleli and Sowah 2022). These models have advantages in addressing serial correlation, endogeneity issues, and second-order bias. The results show that all estimated models have the correct expected signs and are statistically significant, as highlighted earlier by the NARDL results. In other words, the effect of energy productivity on CO_2E in Ireland is negative and significant, i.e., a 1% increase in energy productivity causes CO_2E to decline by −49.094% (DOLS) and 38.629% (FMOLS). These outcomes support H_{o1} of this present study and are in line with the study by Umar et al. (2020). Further, in our second H_{o2} we assumed that financial development has negatively and significantly affected CO_2E in Ireland over the study period. The robustness checks show that 1% changes in financial development will lead to a decline in CO_2E by 29.899% (DOLS) and 18.713% (FMOLS).

In our third H_{o3} presented that the use of primary energy consumption propels the rise in CO_2E in Ireland. In other words, 1% uses of primary energy consumption resources propel CO_2E rise by 119.481% (DOLS) and 116.305% (FMOLS). The outcome supports Oyebanji et al. (2022) paper which expressed that financial sector development has a beneficial influence on CO_2E. Fourth H_{o4}, we assumed that economic growth has a steady increase in CO_2E in Ireland, i.e., every 1% increase in economic growth causes CO_2E to rise to 18.703% (DOLS) and 9.427% (FMOLS). This finding supports the study by Sun et al. (2022). Finally, the result demonstrates that the R-squared value of 0.965685 and Adj. R-squared value of 0.964481 all indicated that our explanatory variables are more robust.

Conclusion and policy implication

Conclusion

People and the environment are most affected by poor environmental quality, it can lead to low productivity and shortened lifespans. The empirical evidence base on the subject is relatively technical, lacks transparency, and is inconclusive. This paper examines the asymmetric and long-run effect of energy productivity on the quality of the environment in Ireland from 1990Q1 to 2019Q4 while controlling primary energy consumption, economic growth, and financial development. To capture the impact of energy productivity on the quality of the environment in Ireland, this study employed nonlinear ARDL techniques. In addition, the Fourier ADL cointegration test and followed the DOLS and FMOLS econometric models were used as baseline robustness checks. The findings of the nonlinear ARDL

Table 6 Robust test

Variable	Coefficient	Std. error	*t*-statistic	Prob
FMOLS				
LGDP	0.094266	0.224060	0.420718	0.6748
LEP	−0.386291	0.214503	−1.800863	0.0744
LFD	−0.187131	0.057774	−3.239026	0.0016
LPEC	1.163048	0.207907	5.594086	0.0000
C	−0.448824	1.189188	−0.377421	0.7066
DOLS				
LGDP	0.187036	0.249554	0.749478	0.4555
LEP	−0.490937	0.237676	−2.065571	0.0417
LFD	−0.298996	0.060573	−4.936080	0.0000
LPEC	1.194809	0.232299	5.143398	0.0000
C	−1.148388	1.323247	−0.867856	0.3878

***, **, and * represent 1%, 5%, and 10% level of significant, respectively

model suggested asymmetric long-run relationships among economic growth, primary energy consumption, financial development, energy productivity, and carbon emissions in Ireland. In addition, the relevant insights of nonlinear ARDL long run form were captured: (a) for energy productivity, the positive and negative shocks have a negative causal effect on carbon emissions in Ireland; (b) similarly, both positive and negative shocks in financial development have a negative causal effect on carbon emission. These results show that energy productivity and financial development are the two major drivers for enhancing the quality of the environment in Ireland, while primary energy consumption and economic growth remain renewing challenges for Ireland's government, according to the time series data covered. Hence, this present paper presents the following recommendation.

Policy recommendations

i. A long-run effect of primary energy consumption and economic growth causing carbon emissions to rise in Ireland is grave. The Irish government should ensure that green growth and clean energy sources drive the economic growth process in Ireland because economic growth, as reported by this study, adversely affects environmental quality. Ireland could suffer from environmental degradation if the excessive growth trend is not eco-friendly regulated. For Ireland to achieve its commitment to reducing its greenhouse gas emission to about 80% and renewable electricity, government authorities are willing to address the following challenges: (a) enforce emitters polluter pays and user-pays principles more effectively, considering external environmental damage implications; (b) improve environmental policies by incorporating economic instruments and monitoring their results more closely; (c) review and better coordination local and central government efforts to implement environmental policies, including European directives, in order to achieve environmental efficiency; (d) prepare and sustain national sustainable development strategy to achieve environmental quality, and (e) one concrete change could be consumers pay fewer taxes for cleaner fuels versus fossil-based fuels.

ii. The Ireland authorities should encourage robust policies environment that drive renewable energy, energy productivity, and patents on environmental technologies. Control pollution, decarbonize transport, encourage innovations for electric vehicles, and other general renewable energy technologies policies that have strong environmental benefits should be adopted. Intensify efforts to decouple waste generation from economic growth. Reduce discharges of oil from offshore oil and gas operations. In order to reduce primary energy consumption, open communication such as newspapers, forum discussions on energy conservation, green initiatives, clean energy, circular economy, green energy, the environmental benefit of energy productivity, and the importance of financial development, among others, should be highlighted and encouraged by policymakers.

iii. Evidence of nonlinear long-run asymmetry relationship demonstrates the continue implement of law on strategic environmental assessments and promotes resource productivity in the context of diversifying the national economy. Policymakers can use this finding to prioritize policies that promote research and development, develop a green package innovation, clean technologies, financial development, and renewable energy sources to combat CO_2 emissions, thus achieving UN 2030s Sustainable Development Goals (SDGs); In particular, SDG 7 and SDG13.

Study limitations and future research suggestions

This study's policy agenda considers energy productivity shifts, while economic growth, financial development, and primary energy consumption were chosen as the contextual variables. Nevertheless, the Ireland situation might be described using a broader set of policy factors, which could be deemed a research constraint. In addition, the policy framework advocated in the research contains features of generalizability and flexibility, and as a result, it may be utilized as a standard for other developed nations. The framework's flexibility enables policymakers in Ireland to modify it to fit its scenario while maintaining the policy purpose. Therein lays the research's significance. Future studies on this topic should consider implementing an asymmetric NPARDL model in a single framework using the quantile regression method to detect asymmetries in a different country environment. Furthermore, the squared term of GDP per capita to check EKC could enhance the outcomes.

Author contribution Dervis Kirikkaleli and James Karmoh Sowah Jr. conducted the investigation and gathered the data. Kwaku Addai wrote the introduction and the literature review, while James Karmoh Sowah Jr. prepared the methodology and the empirical findings as indicated in this paper. In addition, Dervis Kirikkaleli assisted in the explanation of the results. Finally, as the corresponding author, I confirm that the final version of this paper was reviewed and endorsed by all authors.

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Declarations

Ethical approval We declare that this paper is original, has not been published before, and is not currently being considered for publication by another journal. Therefore, this research does not require ethical authorization or informed consent.

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